USE OF THE BENDING BEAM RHEOMETER AS A LOW-TEMPERATURE PERFORMANCE TEST FOR ASPHALT MIXTURES

by

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ABSTRACT

The Bending Beam Rheometer (BBR) test is a recently developed test that is used to determine low-temperature behavior of asphalt mixtures. By knowing the low-temperature behavior, transverse cracking can be effectively predicted. Transverse cracking is a major cause of distress in wintertime and degrades the pavement structure. Significant research has shown that the BBR test can not only be used as a viable means of predicting this type of cracking, but also as a simpler and more economical method to address low-temperature pavement performance. However, as mentioned, the BBR test as used in this regard is relatively new, and needs to have standard specifications developed for the testing of the low-temperature properties of asphalt mixtures. The purpose of this study is to demonstrate both the repeatability and efficiency of the BBR test when applied to asphalt mixtures, in order to promote the development of standard specifications for its use in asphalt mixture low-temperature testing.

The repeatability of the BBR test was verified to ensure that the results of BBR testing were consistent across different labs, different testing intervals, and duplicated tests on the same specimen. This was done by BBR testing a series of beams cut from lab prepared Super Gyratory Compactor (SGC) samples at two different labs. The results indicate that the BBR test is repeatable under the given circumstances.

The widespread adoption of the BBR test requires efficient use of existing materials. Highway agencies prepare SGC samples for volumetric properties verification,

as well as collect field core samples for asphalt pavement thickness verification. The BBR test, as it can use beams from both of these types of already collected samples, can be more easily adopted than other low-temperature tests that require extra samples to be obtained specifically for them.

Both studies provided support for the creation of standard specifications for the BBR test as used in measuring low-temperature properties of asphalt mixtures. In addition, both studies encourage the widespread use of the BBR test as a means of accurately and efficiently measuring these properties.

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CHAPTER 1

INTRODUCTION

1.1 Background

The Bending Beam Rheometer (BBR) is a testing device that is commonly used to determine the low-temperature Performance Grade (PG) of asphalt binders [1] [2]. It provides measurements of both creep stiffness (or creep modulus) and relaxation capacity (m-value) of asphalt binders that can be used to assess the ability of an asphalt binder to resist low-temperature cracking. Creep stiffness is the measurement of the stress-strain-time response of asphalt mixtures [3]. The m-value is the rate of change of creep stiffness versus time on a log-scale, and it represents the capacity of an asphalt mixture to resist cracking by relaxing the stresses [4].

Instead of using the BBR to only evaluate low-temperature properties of asphalt binders, research performed at the University of Minnesota [5] [6] [7] and at the University of Utah [8] [9] has shown that the BBR test is also viable in predicting low-temperature behavior of asphalt mixtures with only small variations in testing protocol from AASHTO T313 [3][10]. An asphalt mixture is a bituminous material and typically consists of asphalt emulsion (binder) and aggregates. The BBR test, as it is used in this regard is relatively recent, needs to have standard specifications developed for the testing of the low-temperature properties of asphalt mixtures. The goal of this study is to demonstrate both the repeatability and efficiency of the BBR test when applied to asphalt mixtures, in order to promote the development of standard specifications for the low-temperature testing of asphalt mixtures.

In order to consider the BBR test for standard specification, the BBR testing results must not only show a relationship to performance in the field, but they must also address both the repeatability of the BBR test across different labs as well as its ability to test samples from different sources so that enough material is available. To evaluate repeatability, samples were prepared and tested at two different locations: the University of Utah lab and the Utah Department of Transportation (UDOT) central lab. This repeatability study's approach is specifically described in Chapter 4, which is a published article from the American Society of Civil Engineers (ASCE) Cold Region Engineering Proceeding [11]. This article addresses in detail BBR repeatability in three ways: repeatability across labs, test intervals, and repeated tests on the same specimen. These experiments verified the repeatability of the BBR test.

The second study in Chapter 5 addresses the other requirement for standard specification, efficient use of existing materials, such as standard cores that were obtained from the road (field core samples) and compacted samples that were prepared in the lab (Superpave Gyratory Compacted (SGC) cylinder samples) for quality control during paving operations. However, because coring leaves a hole on the road, standard field core samples have a diameter of only 100-mm. The length of the specimens that are obtained from these standard 100-mm diameter field core samples are shorter than the BBR testing span length. Therefore, an adjustment procedure was developed to allow the BBR to perform measurements on field core samples. The specimens obtained from

SGC samples, on the other hand, are able to be used for BBR test specification without the need for further adjustment. Chapter 5 demonstrates the ability of the BBR test to predict low-temperature cracking using both SGC samples and field core samples.

Both studies provide reasons and support to create standard specifications for the BBR test as used in measuring low-temperature properties of asphalt mixtures.

1.2 Scope of the Study

This study only focuses on repeatability and material efficiency of the BBR. The BBR was used to measure creep stiffness and m-value of both SGC samples and field core samples. Field core samples were obtained from newly paved roads: SR89, SR172, and I84; SGC samples were prepared in the lab from loose mix obtained at the time of construction of the same roads.

1.3 Objectives

To be considered for a specification and to promote the widespread adoption of the BBR test, this study will specifically focus on:

- Comparing the BBR results between the University of Utah lab and the UDOT central lab on the same sample for verification of the repeatability of the BBR test across labs
- Investigating the BBR test results when samples were tested at different testing intervals
- Performing the BBR test repeatedly on the same specimen, and examining testing results from each set of repeated BBR tests

- Using BBR results from the SGC samples to evaluate the performance of mixes placed in the field
- Investigating the ability to test shorter specimens that obtained from 100-mm diameter field core samples
- Verifying the BBR results from field cores and from lab prepared samples (SGC samples) to assess the likelihood of thermal cracking for field mixes

CHAPTER 2

LITERATURE REVIEW

2.1 Transverse Cracking

Transverse cracking, also known as low-temperature cracking, is caused by the shrinkage of the asphalt mixture layer of pavement due to low temperature. The shrinkage introduces tensile stresses to the asphalt mixture layer. When the applied tensile stress overcomes the tolerance of asphalt pavement, cracks are formed [12]. Pavements with low ability to relax the stresses are more prone to cracking. Transverse cracking is perpendicular to the centerline of the pavement when it appears, as shown in Figure 2-1. As a failure indicator of pavement, transverse cracking not only affects the aesthetic appearance of road pavements, but also seriously degrades the pavement structure. When moisture from rain and snow is introduced into the transverse crack, the deterioration of the pavement structure accelerates [13] [14]. Every year, State Departments of Transportation (DOT) and highway agencies spend significant amounts of time and money to maintain pavements, some of which have undergone this type of cracking. The most commonly used maintenance method is sealing of the cracks with an asphalt emulsion [13].

Figure 2-1. Transverse cracking on asphalt pavement.

2.2 Asphalt Mixture's Performance Evaluation

It is important to evaluate an asphalt mixture's performance in order to prevent any type of degradation of the pavement. Successful performance of asphalt mixtures must consider the properties of the material at both high and low temperatures. However, current specifications have been primarily focused on controlling the warm temperature performance of asphalt mixtures (i.e., permanent deformation) [15]. This has resulted in highway agencies adopting tests such as the Hamburg Wheel Track Test to ensure good high-temperature performance [16].

Adoption of tests for cold temperature properties has occurred at a much slower pace. Research done in the past has shown that low-temperature properties can be controlled through the mix design procedure, binder grade selection, and quality control process [13], since each of them directly or indirectly dominates the properties of asphalt mixture materials. The BBR test has been commonly used to control the low-temperature properties of binders through determining the low-temperature PG [1] [2]. While successful in many ways, this test does not consider some important factors that affect the mix such as: the binder to aggregate interface, aging of the binder that occurs during production, or the addition of recycled asphalt product (RAP) or recycled asphalt shingles (RAS) [8]. Tests such as the Indirect Tension Test (IDT), Thermal Stress Restrained Specimen Test (TSRST), Semi-Circular Bend (SCB) Test, and Disc Shaped Compact Tension (DCT) Test have shown good correlations with low-temperature properties of asphalt mixtures but are not commonly used. The reasons for this lack of low-temperature mixture test adoption are varied but include factors such as difficulties in obtaining and preparing samples, time required for testing, high cost of equipment, and familiarity with the test procedures. These difficulties have prevented the adoption of testing specifications to evaluate asphalt mixtures' low-temperature properties.

2.3 Process of Evaluation of Low-Temperature Performance of Asphalt Mixtures

In order to prevent low-temperature distress and provide more durable pavements, laboratory testing followed by mechanical modeling has been used. Laboratory testing allows researchers to investigate an asphalt pavement's mechanical properties as it responds to low temperatures in samples obtained from either lab gyratory prepared samples or field core samples. The results from laboratory testing are used in mechanical models to simulate viscoelastic behavior of asphalt concrete and predict pavement low-temperature cracking. Mechanical models are developed based on the viscoelastic behavior of asphalt concrete and are used to simulate an asphalt pavement structure's mechanical behavior. Viscoelastic models use mathematical expressions to predict thermal distress. Due to the complexity of asphalt pavement structures, research on different viscoelastic models has suggested that using different models in combination to predict asphalt concrete behavior provides better results [17]. However, for specification purpose, a simplified index parameter is often preferred.

2.4 Current Low-Temperature Performance Evaluation Methods

As mentioned earlier, many tests have been proposed to evaluate the low-temperature properties of asphalt mixtures. However, the IDT and TSRST are the two tests that were developed as part of the Superpave efforts and have been used on limited basis by State DOTs and highway agencies [9].

2.4.1 IDT Test

The IDT test is a method developed during the Strategic Highway Research Program, and it has been standardized under AASHTO T322 and ASTM D6931 [18][19][20]. In general, a temperature-controlled chamber is used to conduct this test. An asphalt mixture cylinder specimen is placed on its side in the chamber (Figure 2-2 [10]). A set of The Linear Variable Differential Transducers (LVDTs) inside the chamber is used to measure the horizontal deformation created by the applied vertical compressive load [10]. The creep compliance can be determined using the measured deformation. While the IDT test is regarded as the most promising test for predicting low-temperature performance of asphalt mixtures [18], there are still some drawbacks that make the IDT test impractical for everyday use. For example, the IDT test requires more material to be performed, and the whole test procedure is very time consuming [10].

Figure 2-2. IDT test setup [10].

2.4.2 TSRST Test

The TSRST test is another test has been used to control the low-temperature properties of asphalt pavement. This test is generally used in the lab to simulate thermal cracking. A tall slender asphalt mixture specimen is placed inside a testing chamber and both ends of the specimen are glued to two platens with an epoxy compound to restrain the specimen [21] (Figure 2-3 [10]). As the chamber cools the specimen down, it starts to contract. This process introduces tensile stress to the specimen. As the temperature continues to drop, the stresses increase until cracking occurs. The chamber records the tensile stress and temperature, and the LVDT ensure there is no deformation. Although this test is effective, like the IDT test, the whole testing procedure is complicated and time consuming, since the specimen needs to be glued before testing for at least 24 hours until the epoxy is cured [10].

Figure 2-3. TSRST test setup [10].

2.4.3 BBR Test

As already mentioned, the BBR (Figure 2-4) has been recently used to determine low-temperature properties of asphalt mixtures, and previous research has also demonstrated that predictions using the BBR test have strong correlations with the predictions of the IDT test [7] [22]. The typical specimens that are used in the BBR asphalt mixture test are obtained from 150-mm lab prepared gyratory cylinders. The test specimens are prismatic beams that are cut from these cylinders. The applied load for asphalt binder specimens based on AASHTO T313 is 980 mN [2]; however, this load is too small to introduce measurable deflections in asphalt mixture specimens. The modification for testing asphalt mixtures consists of increasing the applied load to 4400 mN±50mN, so that useable measured deflections can be obtained [10]. To be consistent with binder protocols, the testing temperature is 10°C higher than the low temperature specified for the binder grade.

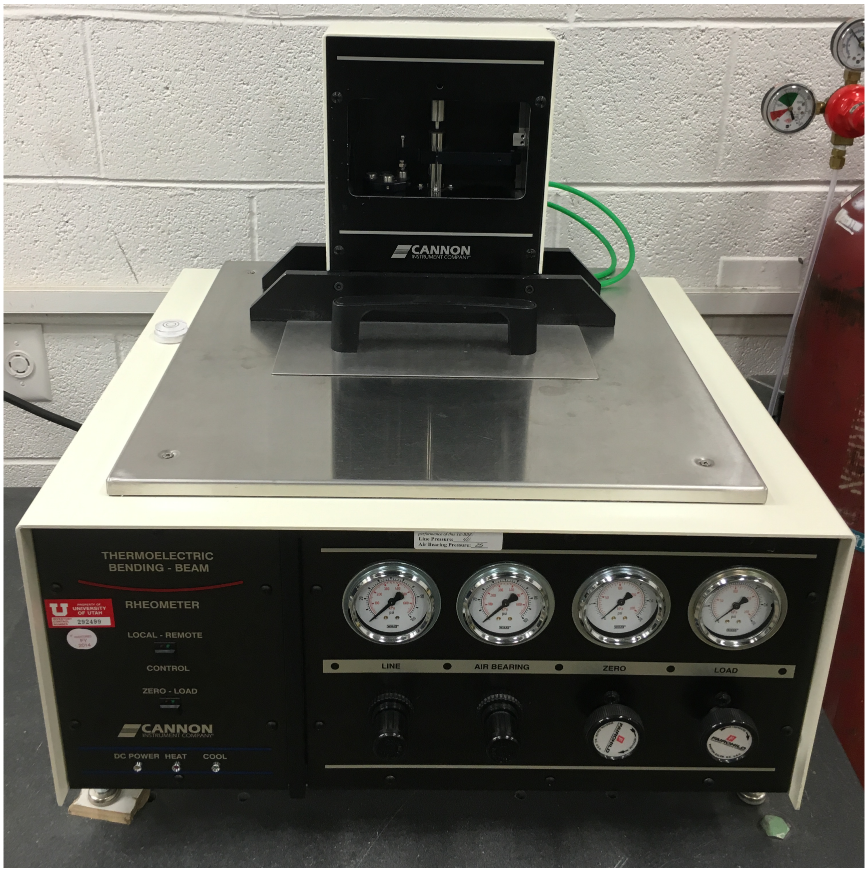

Figure 2-4. Bending Beam Rheometer (BBR).

Concerns of Representative Volume Element (RVE) have also been addressed in past BBR research. RVE is “a certain volume of the composite material that has been determined through calculation and laboratory testing to represent the global properties of the material” [23]. The research done by Clendennen and Romero, and Ho and Romero provided support for the notion that the small testing beam size actually represents an asphalt mixture’s behavior [8, 10, 23]. These studies performed at the University of Utah also concluded that the large aggregate does not introduce variability to the BBR testing results, as the measurement depends on the length of the beam [23].

As introduced earlier, in order to successfully evaluate asphalt mixtures, one must consider the properties of the material at both high and low temperatures. While some asphalt mixtures perform well in warmer seasons, they do not perform as well during the winter, leading to low-temperature cracking. A low-temperature test needs to be standardized for quality control use to prevent low-temperature distress in the winter.

Interest in the BBR test for asphalt mixtures has risen rapidly in recent years [24]. It not only addresses the concerns of the BBR asphalt binder test, but also has more advantages than other low-temperature tests. In the study of Velasquez et al. they concluded that the BBR device is sold at a reasonable price, has well-documented performance, and testing procedures using BBR are simple [24]. Ho and Romero also suggested that "the features of the most promising testing protocol for the day-to-day mix design and Quality Control and Quality Assurance (QC/QA) should be: simple, quick, cheap, and accurate" [8]. These advantages of the BBR test suggest that it is maybe a suitable solution that can be used daily by state DOTs and highway agencies. However, the current BBR test for asphalt mixture protocol is still not a standard specification. More studies are needed in order to prompt the specification of the BBR test.

CHAPTER 3

METHODOLOGY

The methodology of the repeatability and material efficiency studies are explicitly introduced in this section. Detailed sample preparation process and testing procedures are described below.

3.1 Repeatability

The BBR test in mixtures is being proposed as a quality control test; therefore, repeatability across different laboratories is of primary importance. The study of repeatability involves three approaches. First, since the BBR test for mixtures lacks standardized specifications, it is essential to investigate whether or not the BBR test for mixtures can be conducted at different labs for the same asphalt mixtures and still reach the same conclusions. BBR tests were performed at two different labs for a series of SGC samples, and results from both labs were compared for each sample, all of which have the same mix design. In support of the comparison between stiffness measurements from both labs, an unpaired t-test with a significance level of 5% is used to determine if the measurements are significantly different from one another (Appendix). Second, due to practicality considerations, it is difficult to test all samples at the same time; thus, there is a need to investigate how the testing interval (time between specimen fabrication and testing) influences the test results. Samples were tested at four time intervals: 2 days, 3 days, 1 week, and 2 weeks after fabrication. The third approach is to verify that a single specimen can be retested multiple times without compromising the consistency of results. This last experiment is built upon the second approach, as the same samples were tested for each time interval after their initial testing interval as well. The investigation of repeatability ensures that the outcome of the BBR test is reliable for quality control or quality acceptance applications; this provides further support for specification. This study will be detailed in Chapter 4.

3.2 Efficient Use of Materials

Developed specifications, in order to be adopted, require that the test use minimal resources. The minimal resources requirement refers to not only to the low quantity of materials that need to be used in the BBR test, but also that the materials may come from other, already existing sources. The SGC samples and field core samples that are collected by highway agencies as part of their specification can be also used for the BBR test without the need to obtain new samples. However, unlike specimens from SGC samples, the field core samples are usually 100-mm in diameter. Specimens from such diameter are not long enough to be tested with standard BBR setup. In this study, the SGC samples were first tested by the BBR and the results were compared to a transverse crack road survey to find their relationship. As mentioned before, since the BBR cannot directly test specimens cut from 100-mm field core, a procedure was developed in order to use the field cores samples. The results from the field core samples were then compared to the results that were obtained from the laboratory prepared samples for the same mix design. Chapter 5 details how low-temperature mixture testing using the BBR can be accomplished using the same samples that have already been collected.

3.3 Sample Preparation

The asphalt mixture samples that are used in the BBR test can either be obtained from the field (field core samples) or lab (SGC cylinders/puck samples). Most highway agencies collect hot-mix asphalt to make SGC specimens as part of their everyday quality control procedures for volumetric properties. Field cores are also obtained in most projects to verify layer thickness and other properties. Six asphalt mixture SGC cylinder samples (150-mm diameter) were prepared by the UDOT Region 2 Materials lab. Four of these samples were made from one mix used to pave State Road 89; mix designs of the other two SGC cylinders were used to pave State Road 172 (SR172) and Interstate Road 84 (I84), respectively. Three field core samples (100-mm diameter) that were used in research were directly collected from these routes (SR89, SR172, and I84) by the UDOT at the time of construction. All of these samples had the same design binder grade of PG64-28; therefore, based on current practices, they all should have the same low temperature performance. Mix designs were collected for three given state routes and shown in Table 3-1.

Considering that the BBR machine has fix size constraints for its testing setup, all of the specimens need to have length greater than 101.6 mm, which is the span between supports. To obtain samples for testing, field cores and SGC specimens need to be cut into rectangular beams with specific dimensions to meet the testing specimen size requirements (Figure 3-1). The dimensions of samples obtained from the SGC specimen

Table 3-1. Mix Designs for the Given State Routes

State Route	SR89	SR172	I84
NMAS	3/4"	1/2"	3/4"
Sieve	Percent Passing		
1"	100%	-	100%
3/4"	100%	100%	100%
1/2"	87%	94%	87%
3/8"	74%	79%	75%
1/4"	-	60%	-
No. 4	50%	51%	51%
No. 8	32%	32%	33%
No. 16	22%	21%	23%
No. 50	12%	13%	13%
No. 200	6.0%	6.6%	6.2%
Lime Content	1%	1%	1%
RAP Content	20%	25%	25%
Design Number of Gyrations (N_{des})	100	75	100
Percent of Binder (P_b)	4.3%	4.6%	4.7%
Voids in the Mineral Aggregate (VMA)	13.8	14.5	14.0
Maximum Specific Gravity of Mixtures (G_{mm})	2.487	2.502	2.470

are 12.7-mm x 6.35-mm x 127-mm, which are the standard dimensions required by the BBR to test a specimen. However, since the diameter of field core specimen is 100-mm, the maximum length that a sample can be cut from field core beams is only 95-mm, resulting in specimens that are 12.7-mm x 6.35-mm x 95-mm. To be able to test the shorter samples, the supports were moved closer together resulting in a span of 82.7-mm instead of the standard 101.6-mm. The beams were manually cut using a tile saw, based on previous research, the tolerance of dimensions of each beam was ± 0.25-mm [10] [22]. A more detailed description of the fabrication process about how to control the specimen size is detailed in the following study chapters.

Figure 3-1. BBR testing specimens.

3.4 Testing Procedure

The draft specification of the modified BBR developed during previous research provided a very detailed protocol to follow [3]. Before testing each beam, the testing temperature of the BBR bath fluid was controlled by the BBR software. It took about one hour to allow the testing fluid to reach the desired temperature. The testing temperature for all specimens was -18°C, which is 10°C higher than the low PG temperature of the asphalt binder. Methanol was used for bath fluid since it has very low freezing point and has been shown not to affect asphalt properties. According to the BBR manual, a calibration process needs to be implemented after the testing temperature has been reached to ensure the BBR delivers accurate results. The actual dimensions of each beam were measured using digital calipers at three different locations. The average of these dimensions was input into the BBR machine software. Each of the testing beams was then conditioned inside the testing bath for 60 ± 5 minutes. The test beam was then placed on the sample support area of the BBR testing chamber after one hour of conditioning to be tested (Figure 3-2). Once the beam was in placed, the load was applied

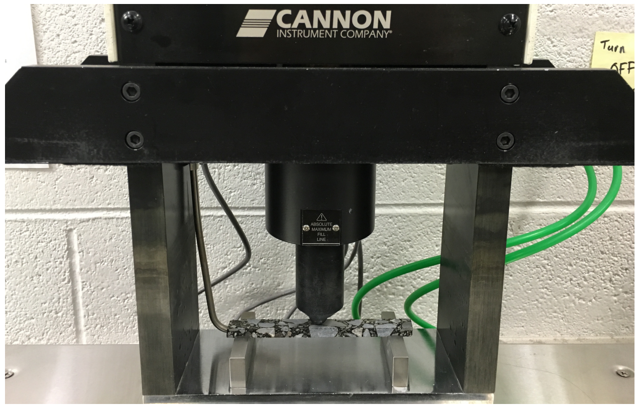

Figure 3-2. Sample support area out of the BBR bath.

and the time-dependent deformation was measured. The BBR software automatically calculated creep stiffness for each beam based on the applied load (4413mN±50mN), and recorded deflection.

In order to test as many samples as possible, each testing beam was placed inside the testing bath on a 13-minute interval. The testing beams were taken from room temperature to the testing bath which has a temperature of -18 °C. Because of this temperature difference, the testing bath temperature fluctuated about +1°C when a new testing beam was put inside the bath. In general, it takes 5 minutes for the BBR to test 1 beam. The 13-minute interval provided an extra 8 minutes to allow the testing temperature to stabilize before the next testing.

3.5 Testing Theory of Analysis

The BBR test is based on Three Point Beam Theory [3] [5]. As shown in Figure 3-3 [10], a concentrated load is applied on the midpoint of the simply supported beam to produce deflection, and this deflection is recorded by the LVDT. The deflection at the

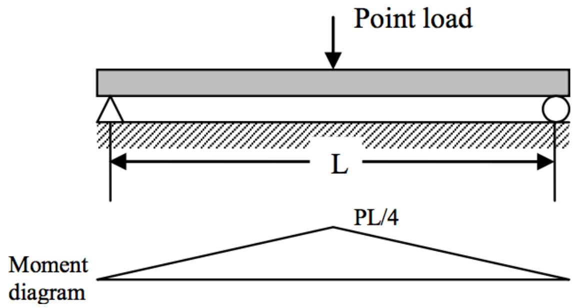

Figure 3-3. Free body diagram of testing specimen [10].

mid-span is expressed as Equation 3-1. The moment of inertia of a prismatic beam can be can be calculated based on Equation 3-2. After substituting the moment of inertia equation into Equation 3-1 and rearranging it, the time-dependent flexural creep stiffness can be calculated according to elastic-viscoelastic correspondence theory (Equation 3-3) [3]. By knowing the span length, the applied load, the measured deflection, and the dimensions of each beam, the BBR can automatically calculate the time-dependent flexural creep stiffness for each time interval using Equation 3-3.

Figure 3-4 shows a constant load applied on the beam. Since the asphalt mixture has a viscoelastic behavior, an instantaneous deflection occurs when the specimen first experiences the load. As the time increases, the deflection also increases (Figure 3-5). Figure 3-6 provided the creep stiffness versus time in a log scale, and is derived from the loading and deflection plot. As shown in Figure 3-6, when the specimen experienced a constant load, its creep stiffness decreased as time went on. The red dashed line in Figure 3-6 indicates the slope of the creep stiffness curve at 60 seconds. As mentioned earlier, the m-value is the rate change of creep stiffness versus time at a certain time, and it can be expressed as the slope of the creep stiffness curve at a specific time.

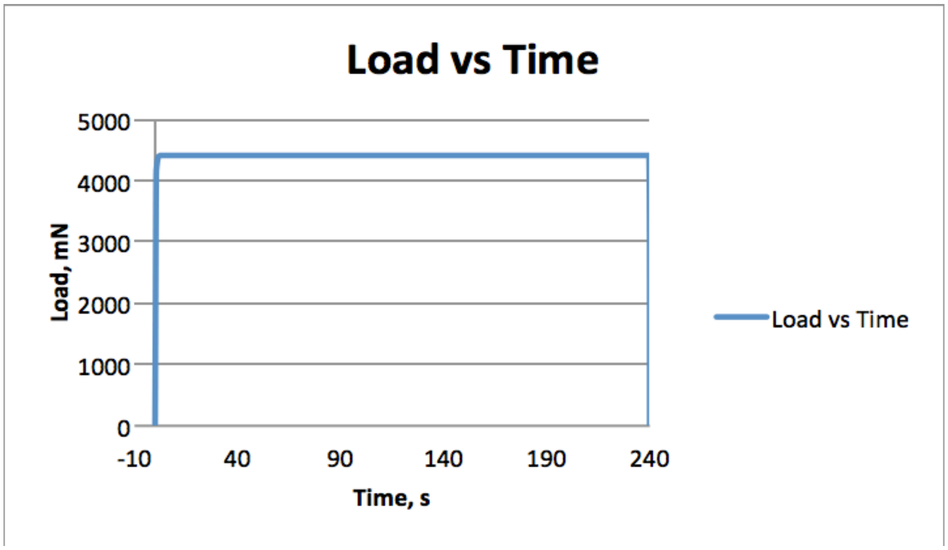

Figure 3-4. Loading on specimen vs. time.

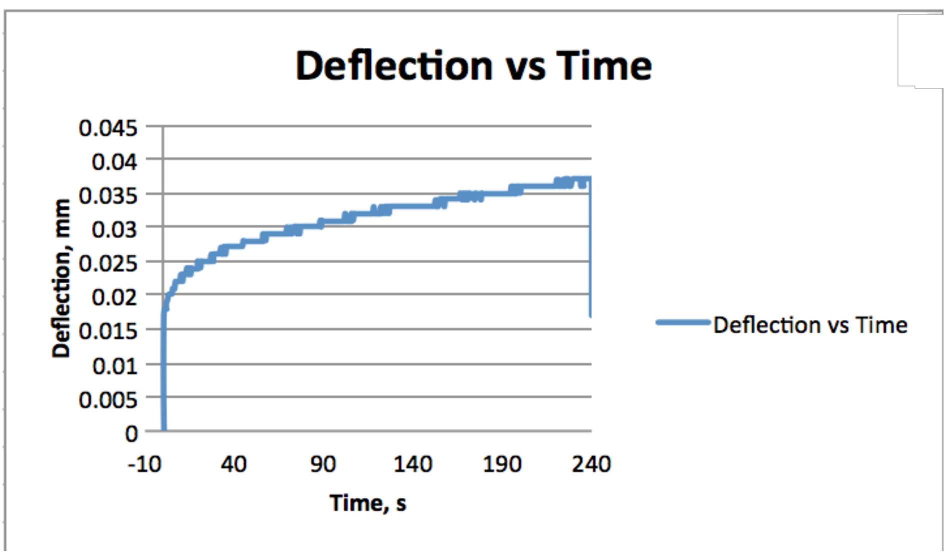

Figure 3-5. Deflection of specimen vs. time.

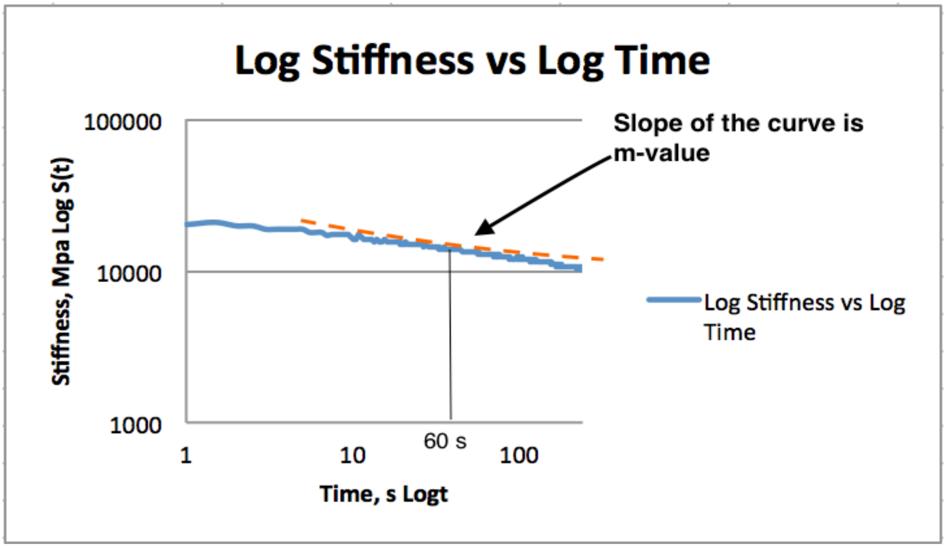

Figure 3-6. Stiffness of specimen vs. time in log scale.

$$\delta = \frac{PL^3}{48EI} \qquad \textit{Equation 3-1}$$

Where: δ = deflection of beam at midspan (mm)

P = load applied (N)

L = span length, mm;

E = modulus of elasticity (MPa)

I = moment of inertia of prismatic (mm^4)

$$I = \frac{bh^3}{12} \qquad \textit{Equation 3-2}$$

Where:

I = moment of inertia of cross-section of test beam (mm^4)

b = width of beam (mm)

h = thickness of beam (mm)

$$S(t) = \frac{PL^3}{4bh^3\delta(t)}$$ *Equation 3-3*

Where:

$S(t)$ = time-dependent flexural creep stiffness (MPa)

P = constant load (N)

L = span length (mm)

b = width of beam (mm)

h = thickness of beam (mm)

$\delta(t)$ = deflection of beam (mm)

CHAPTER 4

REPEATABILITY OF THE BBR TEST

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Repeatability and Reproducibility of Low-Temperature Testing of Asphalt Mixtures Using a Modified Bending Beam Rheometer

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Abstract: Low-temperature cracking is one of the major causes of pavement distress during the winter season. Research has shown that measuring the flexural stiffness of asphalt mixture beams using a bending beam rheometer (BBR) is a good way to control the low temperature properties of asphalt mixtures. However, before such a test is adopted as a specification, the repeatability and reproducibility of the testing protocol need to be verified. This study uses the draft American Association of State Highway and Transportation Officials protocol established by Marasteanu et al. to evaluate the variability of results from two separate laboratories, one at the University of Utah and one at the Utah Department of Utah central laboratory. The purpose of this research is to examine the reproducibility of test results across different laboratories. A series of gyratory asphalt mixture samples were examined based on mixture designs from Utah highways; each of the samples was cut into thin asphalt mixture beams and divided evenly between the two laboratories. Each set of tests shared the same variables for both laboratories and were conducted on the same day. The testing was performed at a temperature of -18°C, which corresponds to the low temperature performance grade plus 10°C. One variable was altered between each pair of tests, namely the amount of time between cutting of the gyratory asphalt mixture sample and running of the test. The variations in time conducted after cutting included four intervals: two days, three days, one week, and two weeks after cutting, which highlight the effects of any steric hardening for both short and long periods on the repeatability of results. The results of these tests demonstrated consistency across both laboratories. These results also indicate that steric hardening has no effect on testing samples after 48 hours and that the test results are repeatable for the same asphalt mixture specimen. Therefore, the BBR test can be used as a low-temperature specification for asphalt mixtures.

Keywords: Asphalt mixtures; Bending beam rheometer; Flexural stiffness; Low temperature; Repeatability.

1 INTRODUCTION

Low-temperature cracking in cold regions has been a major cause of distress for asphalt concrete pavement. Every year, state highway agencies spend significant amounts of time and money to maintain pavement that has undergone low-temperature cracking (Ho and Romero 2012). In order to provide a durable pavement, it is necessary to explore the asphalt mixtures' mechanical properties, and how they respond to low temperatures.

Currently, there are several experimental methods that have been used to evaluate the asphalt mixtures' low-temperature mechanical properties and predict low-temperature distress. These methods include the indirect tensile test (IDT), the thermal stress restraint specimen test (TSRST), and the bending beam rheometer test (BBR). The BBR test, which is normally used for asphalt binders, has been suggested to be a desirable method used in predicting asphalt mixtures' low-temperature behavior, largely because IDT and TSRST require greater time investments and more procedure quality control (Ho and Romero 2012). BBR is normally used to measure the low-temperature stiffness of an asphalt binder according to American Association of State Highway and Transportation Officials (AASHTO) T313 and ASTM D6648 (AASHTO 2009, ASTM 2008). Researchers at the University of Minnesota have shown that the modified BBR test, adopted from the AASHTO BBR binder test, can be used on asphalt mixtures by applying the same methodology (Zofka 2005). Past research has revealed that the BBR test is valid for asphalt mixtures, and the testing specimen size of BBR also meets the representative volume element (RVE) requirement (Romero et al. 2011).

The BBR test also has advantages when compared with the other low-temperature property tests of asphalt mixtures; this is in part because the BBR test only requires a small amount of material for the test in order to ascertain the properties of the material (Ho and Romero 2012). The BBR test can not only be performed on laboratory asphalt concrete specimens, but it can also be used to test field samples (Jones 2013).. Even though the previously discussed research indicates that using BBR to measure the stiffness of asphalt mixtures to predict intermediate and low-temperature properties could be the superior method because of its unquestionable advantages (Zofka 2007), there are still some problems and factors that could affect testing results, which need to be addressed. Since there is not a standardized specification for testing the low-temperature properties of asphalt mixtures using the modified BBR test, more research is needed.

2 OBJECTIVE

As mentioned above, since the current modified BBR test for asphalt mixtures lacks standardized specification, it is necessary to research if this modified BBR test has adequate repeatability within a single set of laboratory tests and reproducibility across multiple laboratories. In order to investigate the BBR test's repeatability and reproducibility, several specific objectives must be addressed:

- *The Reproducibility of the BBR Test Across Laboratories*

Different laboratories with different test operators may arrive at different results. The objective here is to ensure that the BBR test can be performed in multiple laboratories for the same asphalt mixture, and still arrive at consistent results.

- *The Effect of Time Interval on Materials' Low-Temperature Properties*
  The testing time interval is the time between the sample's creation and when it is tested. It will be examined if varying this time interval for a given sample results in different low-temperature properties that perhaps are caused by steric hardening
- *The Effect of Repeated Testing on a Single Specimen.*
  This objective requires the verification of whether a single specimen can be reused across multiple tests without compromising the consistency of the test's results.

3 METHODOLOGY

The modified BBR test that will be used to predict the low-temperature properties of asphalt mixtures is adopted from AASHTO T313/ASTM D6648. The specifications from AASHTO T313/ASTM D6648 state that the BBR test can be used in testing beams of asphalt binder that have been conditioned at the desired temperature (Romero et al. 2011). The BBR test measurements are based upon two strategies: the elastic solution for a simply-supported beam, and the creep compliance behavior. The measurements of flexural creep stiffness *S(t)* and stress relaxation capacity "*m*" of asphalt binders are used to determine the time-dependent deflection (Romero et al. 2011). Both creep stiffness and stress relaxation capacity can be used to control the thermal cracking resistance of asphalt binder (Romero et al. 2011, Bahia and Anderson 1995). It has been demonstrated by research conducted by Marasteanu et al. that the compliance curve from the modified BBR test has a good correlation with the IDT test (Jones 2013, Zofka 2005). This finding indicates the BBR test can at least predict the low-temperature properties of asphalt mixtures as consistently as the IDT. The initial applied load (35mN±10mN) of the BBR is the same for the modified BBR test of asphalt mixtures and the BBR testing of asphalt binders. The applied load after initial loading for the modified BBR test (4413mN±50mN) is higher than the applied load of the BBR test for the asphalt binder (980mN). This is because the value of the applied load of the BBR test for the asphalt binder is too low to be usable in measuring the deflection (Romero et al. 2011). Work done by Romero et al. (2011) has found that the significant deflection of asphalt mixtures can be produced by a load of 450 grams (4413mN±50mN) without exceeding the tolerance of the BBR equipment at the recommended testing temperature. In applying these findings, this study will use an applied load of 450 grams to perform the modified BBR test. The temperature that will be used to condition the testing specimens is 10°C higher than the low temperature specification of the asphalt binder grade. The modified BBR test procedure refers to a draft AASHTO specification developed by Marasteanu et al. (2009).

The asphalt mixture pucks to be tested were made using the Superpave Gyratory Compactor (SGC). The BBR test requires that a specimen have dimensions of 12.7 mm x

6.35 mm x 127 mm (width x thickness x length) (Jones 2013). As the machine requires rectangular prisms of these particular dimensions, the pucks must be cut into a number of beams that satisfy the size constraints. The beams were cut based on the procedure shown in the draft specification (Marasteanu et al. 2009). In order to guarantee that the dimensions of each beam were consistent, a template was developed to check the width and thickness of the beam. The template had two slots, one slot was used to check the width of beams, and the other slot was used to check the thickness of beams. The dimensions of thickness and width for each beam must be within an acceptable range of ±0.25mm (Romero et al. 2011, Jones 2013). While the beam dimensions are occasionally smaller than the aggregate, this has been shown to have no effect on testing accuracy (Clendennen and Romero 2012). Three asphalt mixture pucks were made from the same mix design, resulting in three identical pucks. Each puck was then cut into 20 beams of the above-mentioned size on the same day. The beams, after creation, were then immediately stored in a sealed container in order to prevent any moisture changes to the beam that would result from exposure to the air. Of the resultant 60 beams, 40 were chosen at random to be used in this study. These 40 beams were then randomly divided in half: 20 of the beams were used in the University of Utah (UofU) laboratory, and 20 were used in the Utah Department of Transportation (UDOT) laboratory. The time at which the beams were cut was recorded, and the BBR test was performed at certain intervals of time past the time of cutting. These intervals were: two days (48 hours), three days (72 hours), one week, and two weeks; plus or minus 10% of that interval's total duration to allow for slight variation in time available for testing. As there were four intervals to be tested, each laboratory's set of 20 specimens was divided into four groups of five specimens. One group of five was tested at each interval. In addition to these tests run by both laboratories, the UofU laboratory ran tests not only of the group to be tested at each interval, but also the groups that were tested at previous intervals again at each new interval. The BBR test results were compared for each relevant group between the laboratories and additionally the extra tests run at the UofU laboratory were compared to the main series of tests for each interval.

4 MATERIALS

All three asphalt mixture pucks were prepared by the UDOT region 2 laboratory for volumetric verification and quality control of State Road 89. These pucks were made from one mix design based on that used for State Road 89, with a design binder grade of PG64-28. The aggregates used for this design were locally sourced. The mixing temperature was 333°F-342°F, and compaction temperature is 312°F-322°F. These samples were taken from the field mix, but compacted in the laboratory. The specific mix properties of this design can be found in Table 1.

All beams of each group and each experiment were tested at one temperature (-18°C). This temperature was 10°C higher than the low temperature of Binder Grade. For each BBR test, measurements of stiffness and m-value were recorded at two loading times, 60s and 120s, by using the time-temperature superposition principle this corresponds to test

Table 1. Mix Design Properties

Nominal Maximum Aggregate Size	3/4"	**Material Description**	**Percent**
Gradation		**Washed Sand**	7%
Sieve Size	**Passing**	**1/8" Unwashed Fines**	12%
1"	100%	**1/4" Unwashed Chip**	15%
3/4"	100%	**1/2" Unwashed Rock**	20%
1/2"	87%	**3/4" Unwashed Rock**	25%
3/8"	74%	**3/4" Milled Reclaimed Asphalt Pavement (RAP)**	5%
No.4	50%	**1/2" Crushed RAP**	15%
No.8	32%	**Lime**	1%
No.16	22%	**RAP Content, %**	20%
No.50	12%	**Binder Content, %**	4.30%
No.200	6%	**RAP Binder Content, %**	1.10%
		Virgin Binder Content, %	3.20%
Air Voids, %	3.70%	**Binder Grade**	PG64-28
VMA, %	13.80%	**Design Gyratory**	100

results at two temperatures or testing of mixtures made with softer binders. These two loading times are also the typical loading times used in studying field data.

5 RESULTS AND DISCUSSION

This study's focus is on analysis of stiffness and m-values of the asphalt mixture. The BBR will automatically record the applied load and deflection of each specimen. The BBR output files include the calculated stiffness and m-value. With the outcome of the BBR test, the data can be collected and analyzed for each experiment. The m-value is the slope of the stiffness-time dependent curve. With the load, deflection, and measured dimensions of each specimen, the linear viscoelastic stiffness modulus can be obtained according to the elastic-viscoelastic correspondence principle. Equation 1, used to calculate the stiffness, is shown below:

$$S(t) = \frac{PL^3}{4bh^3\delta(t)} \quad [1]$$

where: $S(t)$ = time-dependent flexural creep stiffness (MPa), P = constant load (N), L = span length (mm), b = width of beam (mm), h = thickness of beam (mm), $\delta(t)$ = deflection of beam (mm), and $\delta(t)$ and $S(t)$ indicate that the deflection and stiffness, respectively, are functions of time.

5.1 Multi-Laboratory Comparison

The first experiment was to compare the test results of stiffness and m-value of the asphalt mixture specimens between the UofU laboratory and the UDOT laboratory. There were 4 BBR tests performed by each laboratory, one at each interval (2-day, 3-day, 1-week, 2-week). Each BBR test included 5 replicated specimens. The stiffness and m-value at 60s and 120s were analyzed. As each test involves five samples, there are five m-values and five stiffness values. In order to use these values in comparisons between tests, they must be simplified into single values for each test. This was done by first determining the Coefficient of Variance (CV), which is the ratio between the standard deviation and the mean of the five values. If this CV is too high, then the specimens with the highest and lowest deviations are removed as outliers. Once this has been done, or if the CV is within 10% and no such outliers require deletion, then the mean of the values is recorded to be used in comparisons with other tests. If, after the deletion of outliers, the CV of a set of values is still above 10%, the mean is still used without any further deletion. The stiffness and m-value percent difference between the UofU laboratory and the UDOT laboratory is illustrated in Figure 1 below. Figure 2 and Figure 3 show the stiffness and m-value variations over different test intervals of each laboratory.

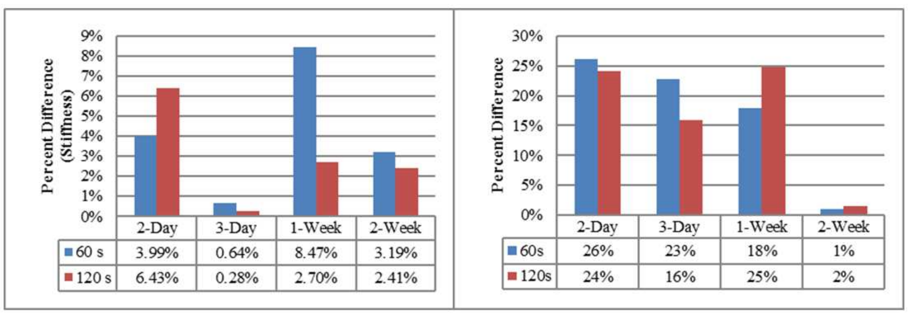

Figure 1. Stiffness and m-value percent difference between UDOT and UofU.

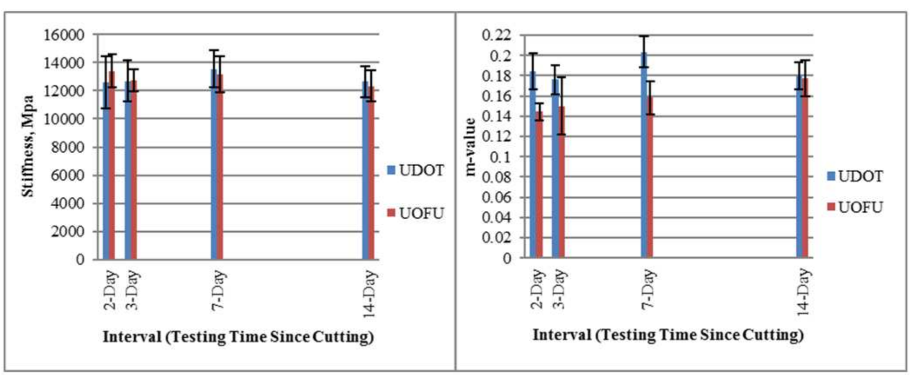

Figure 2. Stiffness and m-value variation for both laboratories over different test interval at 120s.

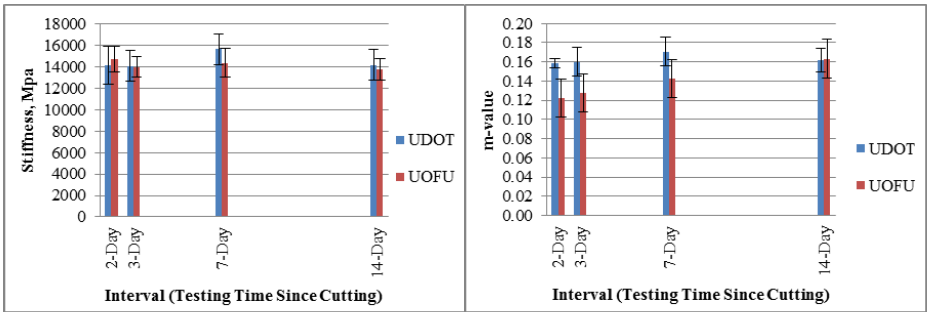

Figure 3. Stiffness and m-value variation for both laboratories over different test interval at 60s.

As shown in Figure 1, the percent difference of the stiffness at 60s and 120s between the UofU laboratory samples and the UDOT laboratory samples for all BBR tests at each of the 4 intervals are below 10%. In order to ensure the BBR test has reproducibility across both laboratories, AASHTO T313 suggested that for multi-laboratory experiments, variation between stiffness should be at or below 17.8% (AASHTO 2009). This indicates the two test results for creep stiffness from two laboratories are within the acceptable range for multi-laboratory precision. In addition, the highest percent difference of stiffness between the two laboratories is around 8.5% for the 1-week interval test at 60s; this is half of the multi-laboratory precision acceptable range. This finding indicates the stiffness measurements using the BBR test between two laboratories are consistent. Figure 2 and Figure 3 show the stiffness variation for both laboratories for different interval tests at 60s and 120s. For both figures, there is no obvious difference in the stiffness measurements across both laboratories. The error bar was plotted on both figures based on the standard deviation that was calculated according to lowest percentage of CV from each group of samples. Considering this error bar, both figures show very consistent results for stiffness measurements for both laboratories. The m-value percent difference for the 2-day interval test, the 3- day interval test, and the 1-week interval test between both laboratories in Figure 1 have large differences at 60s and 120s. The m-value percent difference for the 2-week interval is within 2% at 60s and 120s. The m-value variation for both laboratories for the interval test at 60s and 120s in Figure 2 and 3 show the m-value is not consistent across both laboratories' measurements. By observing the error bar for each laboratory's results, the results from the UofU laboratory have higher standard deviation than that of the UDOT laboratory. This indicates that the results of each interval test for the UofU laboratory have higher variation, which is possibly caused by variation in the fabrication of each specimen. The higher variation of m-value results also cause the comparison for both laboratories to be out of the acceptable range. The allowable range of m-values for multi-laboratory precision was 6.8%, which was suggested by AASHTO T313 (AASHTO 2009). However, the m-value percent difference for the 2-week interval test is within the multi-laboratory precision acceptable range. This indicates that the results may not be entirely conclusive for m-value.

5.2 Testing Intervals Comparison

More BBR test results were analyzed between multiple intervals to investigate the influence of different amounts of time from the creation of the puck to the measurement of stiffness and m-value. Figure 4a-4b and Figure 5a-5b demonstrate the trend of stiffness and m-value varying with testing interval. An additional comparison was made between stiffness and m-value between each test interval and 2-day test interval to again analyze the effect of test interval on the stiffness and m-value. Figure 6 illustrates the percent difference of stiffness and m-value between the 2-day interval test and the 4 interval tests.

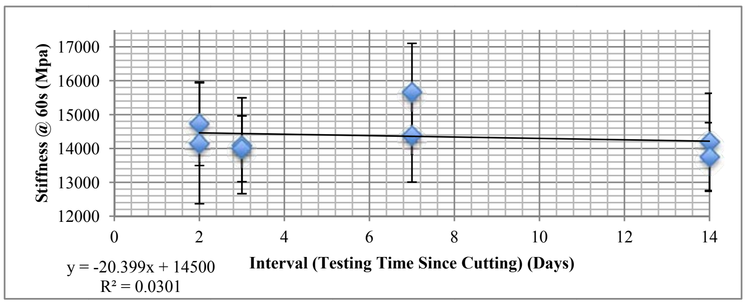

Figure 4a. The trend line of stiffness variations at 60s.

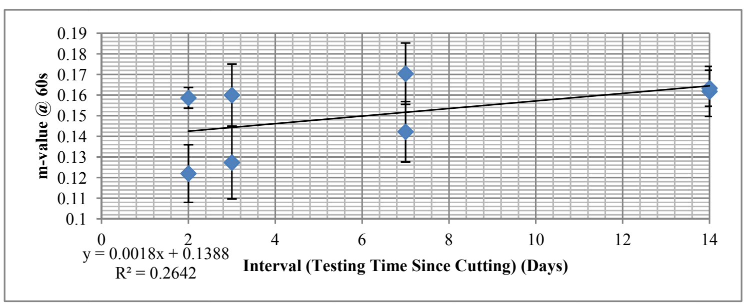

Figure 4b. The trend line of m-value variations at 60s.

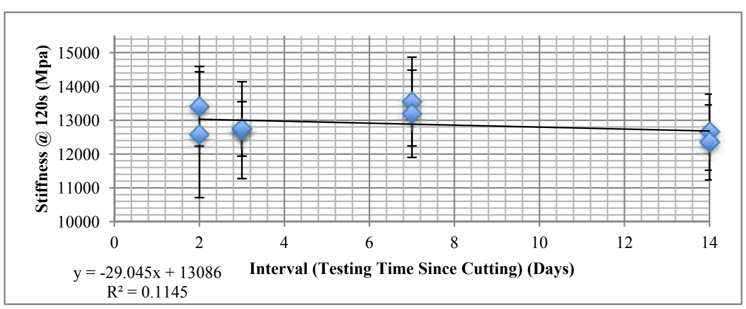

Figure 5a. The trend line of stiffness variations at 120s.

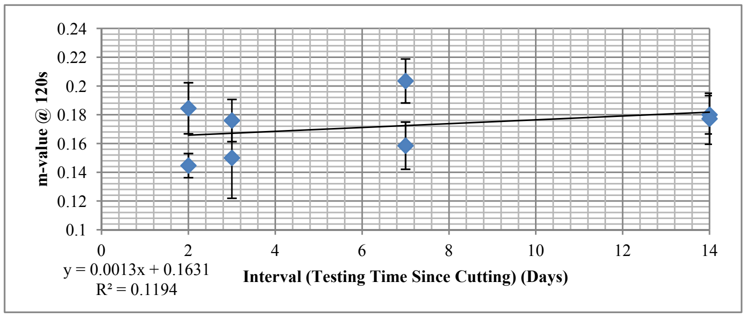

Figure 5b. The trend line of m-value variations at 120s.

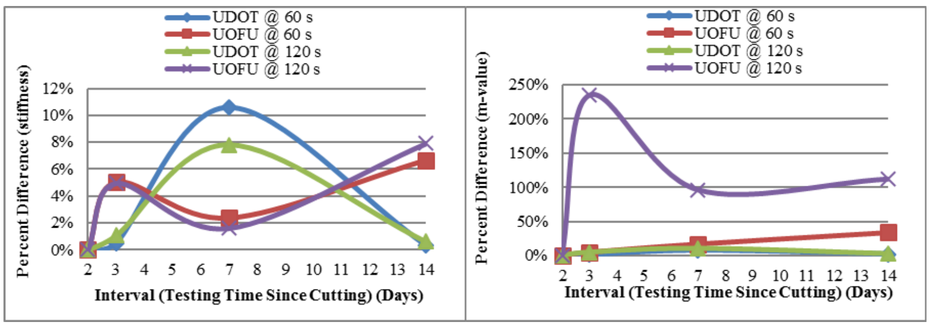

Figure 6. Stiffness and m-value percent difference of each interval test refer to 2-day interval test.

Figure 4a and Figure 5a show the stiffness measurements using the BBR test for 4 different interval tests at 60s and 120s. The trend line in both figures shows the stiffness measurements slightly decreased at longer intervals. However, the R-value for each trend line was very small and did not provide evidence that the trend line fit the data set particularly well. The same phenomenon occurred for the m-value measurements. In Figure 4b and 4b, the m-value slightly increased for longer intervals at 60s and 120s with a trend line with small value of R. Both stiffness measurements and m-value measurements did not show a clear relationship with the testing interval. “Age hardening or steric hardening in an asphalt occurs rapidly at first but appears to approach a limiting degree of hardness on prolonged standing (Barth 1962, Grant 2001).” Since all samples were prepared to be tested 48 hours after the puck was made, the mechanical properties for the asphalt mixtures tended to be more stable. This lead to the testing interval having very little effect on the measurements of stiffness and m-value. In order to identify the testing interval’s effect, the BBR test must be performed within a very short time right after the samples were made. This increases the difficulty of the BBR test because of the intensive time constraints. Figure 6 shows the stiffness and m-value measurements for each interval for both laboratories at 60s and 120s compared with the 2-day interval measurements. Both figures exhibit some amount noise, which indicate that the testing interval does not have a significant effect on the m-value and stiffness results, as there is no effect of steric hardening.

5.3 Repeated Testing on UofU Samples

The 2-day interval test samples were repeatedly tested at the 3-day interval, 1-week interval and 2-week interval, while the 3-day interval test samples were again tested at the 1-week interval and the 2-week interval. Figure 7 and 8 show the stiffness and m-value for the repeat test of 2-day interval test samples and 3-day interval test samples respectively. Not only were the results of each actual testing interval examined (i.e. the specimen first examined at that interval), but the results of groups from prior interval tests that were again run at the new interval were also compared to the subsequent actual test. Table 2 shows the percent difference of stiffness and m-value between the results of each actual testing interval and the repeated test at that corresponding interval.

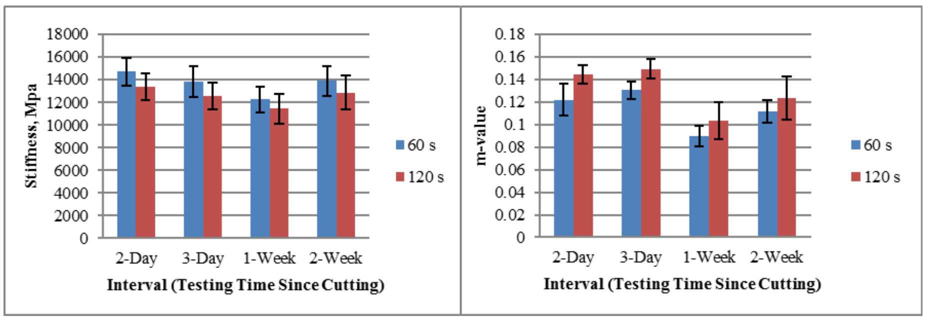

Figure 7. Stiffness and m-value of repeated 2-day interval test samples.

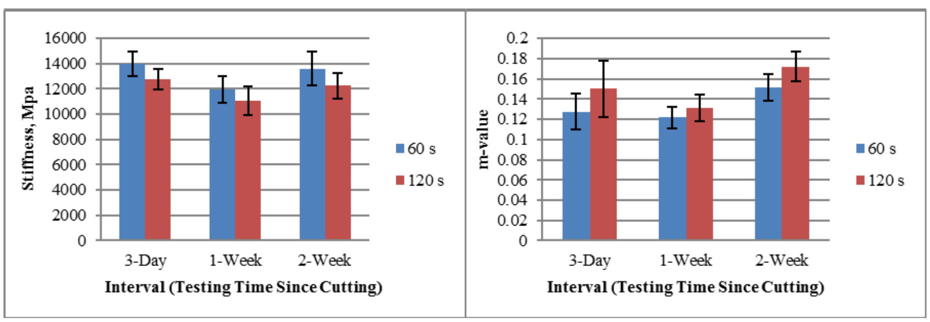

Figure 8. Stiffness and m-value of repeated 3-day interval test samples.

Table 2. Summary of Percent Difference of Results for Repeated Test Samples

	60s		**120s**	
	Stiffness (Mpa)	**m-value**	**Stiffness (Mpa)**	**m-value**
Actual 3-Day Interval Test	13992.18	0.13	12743.61	0.15
2-Day Interval Samples Tested at 3-Day Interval	13814.24	0.13	12545.29	0.15
Percent Difference	1%	3%	2%	0%
Actual 1-Week Interval Test	14381.85	0.14	13193.46	0.16
2-Day Interval Samples Tested at 1-Week Interval	12259.10	0.09	11449.96	0.10

Percent Difference Refer to 2-Day Interval Samples	16%	45%	14%	42%
3-Day Interval Samples Tested at 1-Week Interval	11959.49	0.12	11064.88	0.13
Percent Difference Refer to 3-Day Interval Samples	18%	16%	18%	19%
Actual 2-Week Interval Test	12346.34	0.16	13749.79	0.18
2-Day Interval Samples Tested at 2-Week Interval	13901.28	0.11	12867.57	0.12
Percent Difference Refer to 2-Day Interval Samples	12%	38%	7%	36%
3-Day Interval Samples Tested at 2-Week Interval	13614.40	0.15	12250.74	0.17
Percent Difference Refer to 3-Day Interval Samples	10%	7%	10%	3%
1-Week Interval Samples Tested at 2-Week Interval	13597.89	0.13	12632.59	0.14
Percent Difference Refer to 1-Week Interval Samples	10%	22%	8%	25%

The 2-day interval test specimens and 3-day interval test specimens were repeated at different test intervals. Figure 7 and 8 show the stiffness measurements at 60s and 120s for repeat tests of the 2-day interval specimens and 3-day interval specimens. Based upon these Figures, there is not an obvious difference over repeat testing for either the 2-day interval test specimens or the 3-day interval test specimens. In Table 2, the comparisons between each test run at a given interval are shown, i.e. the 3-day interval compares the results from the actual 3-day specimens and the 2-day specimens that were again tested at the 3-day interval. This shows that the percent difference (the comparison of the results of the actual interval's specimen vs. the repeat specimens) for the stiffness at the 3-day and 2-week intervals for 60s and 120s were around or below 10%, while the percent difference at the 1-week interval is higher. This means that the stiffness measurements for a single beam are quite repeatable using the BBR test. In Figure 7 and 8, the m-values are given in the same format. However, the m-values have large variation for the repeated 2-day and 3-day interval specimens. For m-values, the 3-day interval had a percent difference of 5% for 60s and 120s between the actual 3-day specimen and the 2-day specimen. The other intervals, 1-week and 2-week, have very large percent differences between repeated specimens and the actual interval specimen.

6 CONCLUSION

Based on the results of this investigation into the repeatability and reproducibility of the modified BBR test on asphalt mixtures, the following conclusions can be drawn:

1. The BBR test has reproducibility across multiple laboratories for quantifying the low temperature performance of asphalt concrete;
2. Steric hardening has no effect on BBR test results after 48 hours, since measurements of stiffness and m-value did not vary with the time interval;
3. The BBR test can be repeated on the same beam without compromising its consistency, as long as testing is done at the proper temperature (10°C above low PG temperature); and
4. Stiffness has less variation than m-value.

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CHAPTER 5

MATERIAL EFFICIENCY OF THE BBR TEST

5.1 Performance Evaluation of Field Mixes Using SGC Samples

The three state routes (SR89, SR172, and I84) were evaluated using Roadview Explorer. Roadview Explorer is an online data collection system which contains information for all state routes in Utah. The original pretreatment condition for all sections was very similar and all three routes received a 2-inch mill and asphalt overlay treatment in 2013. Roadview film is available for these routes for 2014, only one year after treatment. Of the three routes, only one shows transverse thermal cracking, whereas the other two showed none. This information is summarized in Table 5-1. Figure 5-1 and Figure 5-2 show the two transverse cracks on route I84.

Table 5-1. State Route and Survey Data

State Route	UDOT Mileage	RAP Content	Date of Treatment	Date of Survey	Number of Thermal Cracks	Approximate Elevation (ft)
SR89	379.88 – 381.50	20%	July, 2013	March, 2014	0	4,200
SR172	4.49 – 6.04	25%	July, 2013	April, 2014	0	4,200
I84	119.04 – 119.51	25%	May, 2013	April, 2014	2	5,400

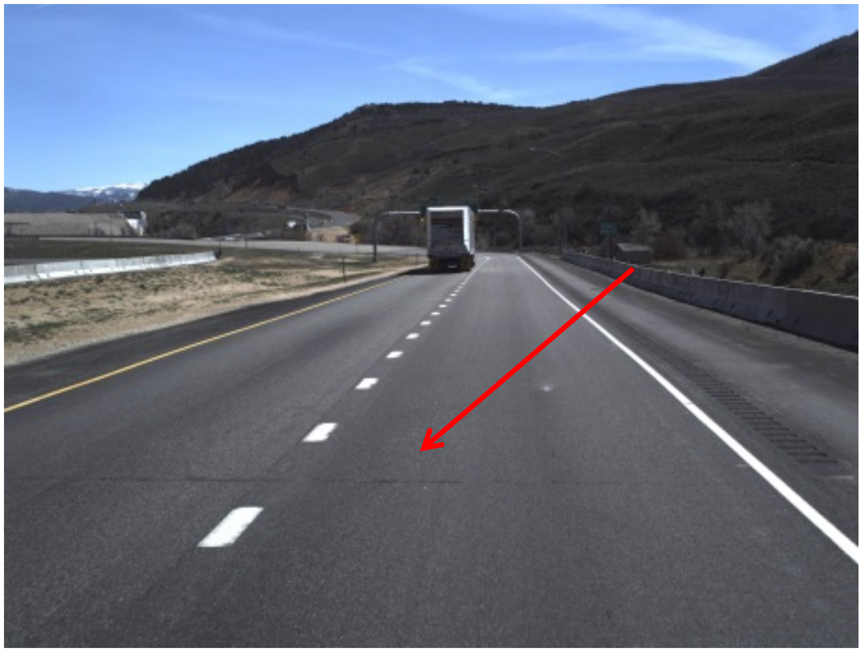

Figure 5-1. Transverse crack at mileage 119.22.

Figure 5-2. Transverse crack at mileage 119.24.

Ten asphalt concrete beams were cut from each SGC cylinder. The SGC samples for routes SR89, SR172, and I84 were tested at -18°C, and -12°C using the BBR. Both creep stiffness and m-value were calculated at 60 seconds of loading. A Black Space diagram was developed to identify the relationship between creep stiffness and m-value (Figure 5-3). A black space diagram is typically used to relate a shear modulus and phase angle. When asphalt is tested at low temperatures, it has very low phase angle. In this case, the creep stiffness and m-value of the BBR measurements are reasonable substitutions for shear modulus and phase angle in the Black Space Diagram [25] [22]. The values are presented at -12°C to be consistent with previous work.

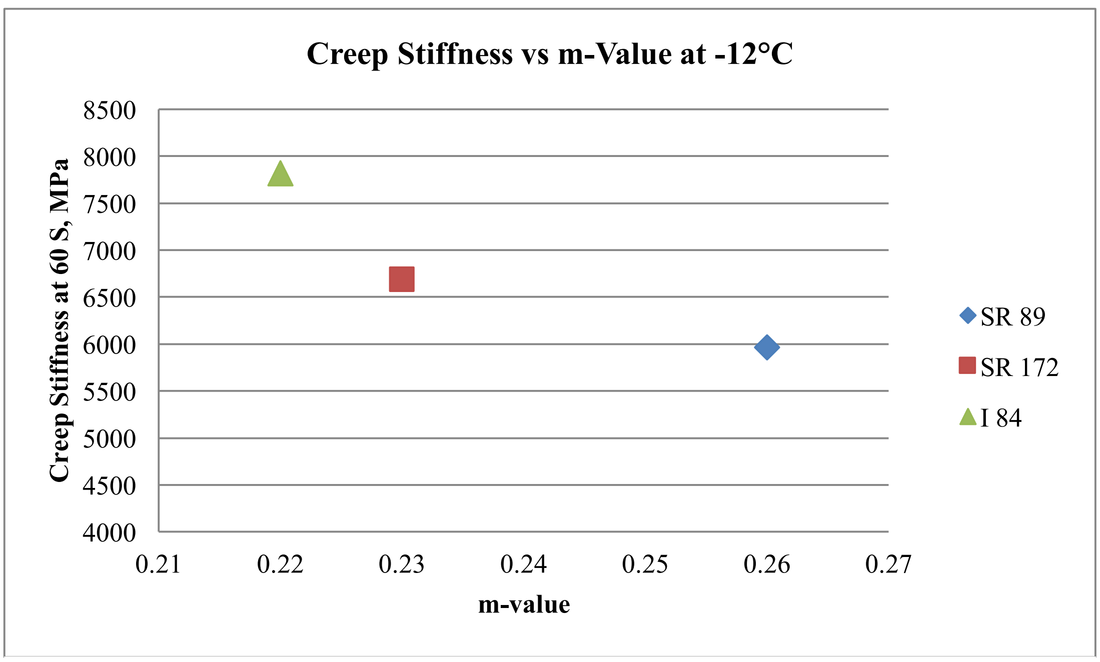

Figure 5-3. Black space diagram for lab compacted samples.

Research done at University of Utah has shown that asphalt mixtures with high creep stiffness and low m-value are more likely to present thermal cracking [22]. This finding was based on analysis of field core samples of pavement sections located throughout the State of Utah. As shown in the previous section, the section of I84 was the only route that found transverse thermal cracking present after only one year of service, while the other two routes showed no transverse thermal cracking. As can be seen, in Figure 5-3, the I84 Sample has the highest creep stiffness and lowest m-value. This verifies the findings of the previous research [22] and demonstrates that BBR testing of asphalt mixtures is a viable method to evaluate low temperature performance.

While the results shown in Figure 5-3 are encouraging with the field performance matching results from the lab tests, it is recognized that the sample population is small. More data are needed to establish a threshold value for stiffness and m-value measurements between field and lab. The elevation of I84 exceeds that of the other two routes by more than 1,000 ft. This elevation difference alone could account for the cracking. More samples and field performance results are needed to explore this issue further and eventually develop a limit.

One way of obtaining more samples for testing would be to take cores directly from the road itself. Because highway agencies are concerned with road performance, it is undesirable to drill too many cores. As previously explained, current quality acceptance protocols require to drill 100-mm diameter cores to verify pavement thickness. From these cores, BBR test samples can be cut and tested. This would provide additional material for testing without occurring additional cost or leaving more holes on the newly paved road surface.

5.2 Testing of Samples Obtained from 100-mm Cores

The standard samples tested in the BBR are 12.7-mm x 6.35-mm x 127-mm (width x thickness x length). The SGC cylinders have a diameter of 150-mm. When samples are obtained from SGC cylinders, the resulting beams have a length of 127-mm and are therefore of adequate length for testing in the BBR setup. Field cores used for thickness verification have a smaller diameter of 100-mm. Beams obtained from these samples have a length of about 95-mm. This length is shorter than the length of the BBR supports of 101.6-mm. Because of this, two additional supports must be placed at both sides of testing platform, flush with the interior edge of the existing supports and resulting in a span of 82.7-mm. Due to this change in the span length of the testing supports, the BBR test results must be adjusted prior to being used in analysis. As will be shown, while simple beam theory should provide the answer, differences in geometry lead to different results. Furthermore, the BBR software assumes a span length of 101.6-mm; thus, to simplify the process, an equation was developed to translate the BBR results straight from the screen and thus facilitating the use of 100-mm cores.

Ten testing beams were again cut from each of the three SGC cylinders used for the predictions in the previous section (i.e., one cylinder for each road section). The BBR test was run twice at -18°C for each of the resultant 30 testing beams. The first time testing was done using the standard supports with a span of 101.6-mm; the second time testing was done using a shorter a span of 82.7-mm. There were a total six sets of BBR tests performed: two sets for each of the three SGC cylinders, one at each span length. The results from each set were then compared between the samples from the same SGC cylinder at the two span lengths, resulting in three final comparisons.

The creep stiffness of long beams is considered the “true” creep stiffness of samples measured using BBR. When beams with shorter span length are tested, the shortened span length of 82.7-mm was substituted into Equation 3-3 to obtain the “adjusted” creep stiffness of each measurement with the different spans. Because two measurements were performed on the same beam, the creep stiffness for measurements with shorter span was expected to be equal to the creep stiffness for measurements with the standard span. However, in comparing the creep stiffness measurement for both sets of experiments, the creep stiffness for samples with shorter spans was significantly lower than the creep stiffness for samples with regular spans. In Table 5-2, the percent difference between creep stiffness from shorter spans and creep stiffness from regular span was found to be around 30%. This indicates that the stiffness from shorter spans cannot be used as a measurement of the creep stiffness from regular span. It should be noted that research done at the University of Utah showed that, as long as the strain in the beam is below 550 microstrains during the entire duration of the test, the BBR test can be performed on a single sample multiple times without compromising the consistency of results [11]; therefore, the observed discrepancy cannot be attributed to repeated testing.

Table 5-2. Comparisons Between 101.6-mm Span Stiffness and 82.7-mm Span Stiffness at 60s and -18°C

Samples	**102-mm Span Stiffness (MPa)**	**83-mm Span Stiffness (MPa)**	**Percent Difference**
SR89	9845.6	6838.5	36%
SR172	10451.9	7596.6	32%
I84	9915.0	7636.9	26%

An equation to obtain the corrected creep stiffness for samples with shorter spans was developed. The stiffness ratio and stiffness difference for each related pair of BBR tests can be plotted versus time (Figure 5-4 to Figure 5-6). Each pair includes the ratio between true stiffness (101.6-mm span) and alternate stiffness (82.7-mm span). A trend line was calculated for each plot. By comparing the trend lines and scattered data between the stiffness ratio and stiffness difference plots, it is apparent that the stiffness difference trend line is a better fit to the scattered data. Upon further inspection, the trend line for difference between true (101.6-mm span) and alternate stiffness (82.7-mm span) are more likely represented by a logarithmic equation. As each stiffness difference plot is represented by a logarithmic equation, the coefficient and constant of each trend line equation were averaged for use in a new logarithmic equation. This new equation represents the difference between 82.7-mm span stiffness and 101.6-mm span stiffness over specific times (Table 5-3). After evaluation of the data, the 'true' stiffness is equal to the 82.7-mm span stiffness plus the equation of difference between stiffness values, as shown in the Equation 5-1.

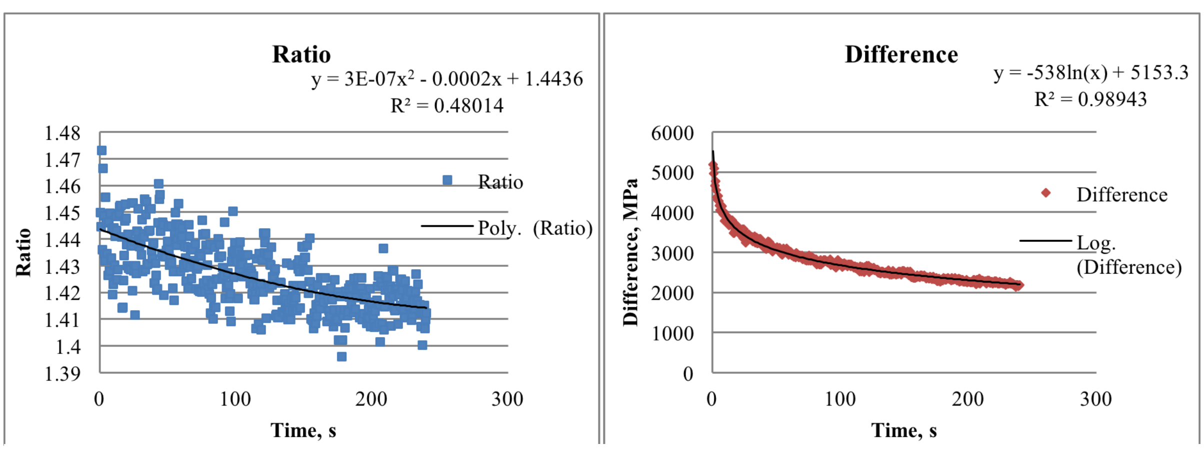

Figure 5-4. Stiffness ratio and stiffness difference for SR89 at -18°C.

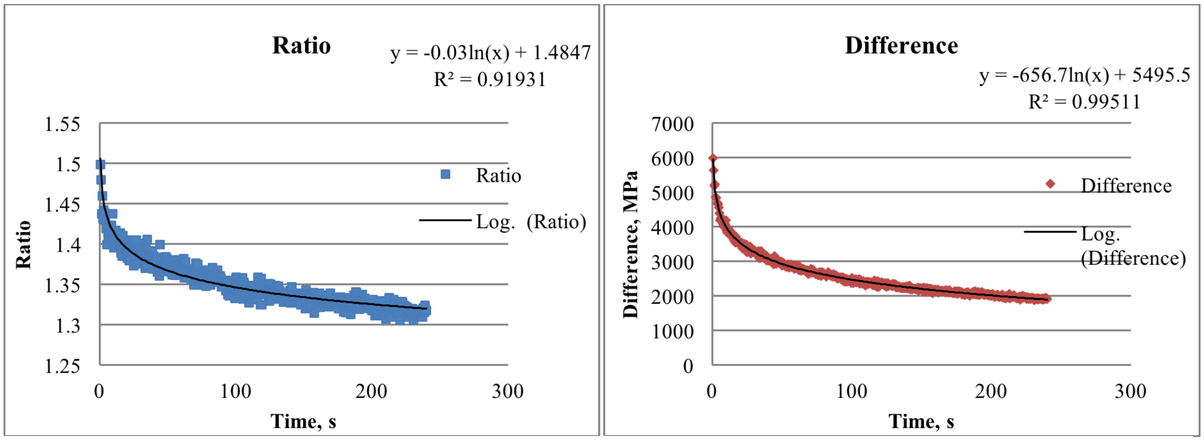

Figure 5-5. Stiffness ratio and stiffness difference for SR172 at -18°C.

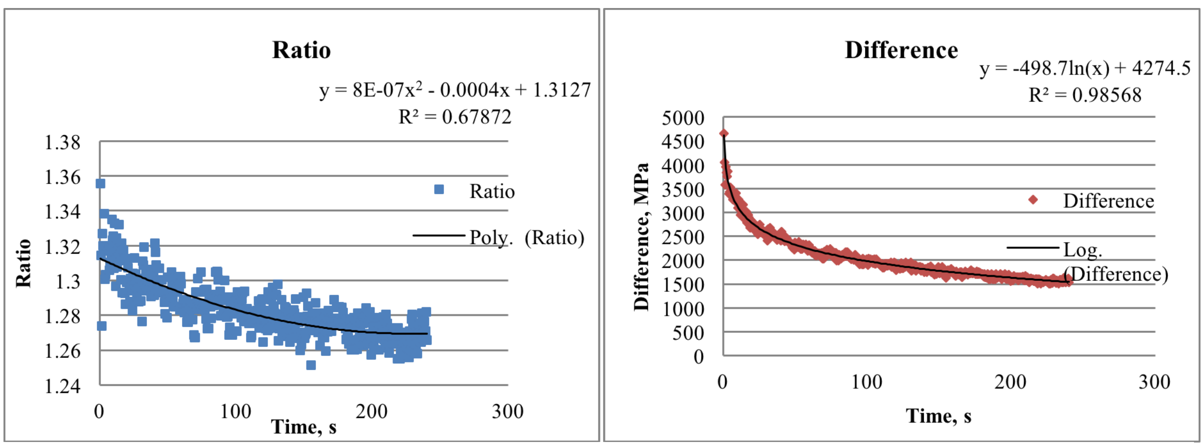

Figure 5-6. Stiffness ratio and stiffness difference for I84 at -18°C.

Table 5-3. Summary of Stiffness Difference Trend Line Equation

Name	Stiffness Difference Trend Line Equation	Coefficient	Constant
SR89	y = -538ln(x) + 5153.3	-538.0	5153.3
SR172	y = -656.7ln(x) + 5495.5	-656.7	5495.5
I84	y = -498.7ln(x) + 4274.5	-489.7	4274.5
Average	y = -561.5ln(x) + 4974.4	-561.5	4974.4

$S_{CS}=S_{AS}+S_d$ *Equation 5-1*

Where: S_{CS} = Corrected Stiffness (MPa)

S_{AS} = Adjusted Stiffness (MPa), $S_{AS}=S_{TS}*\frac{82.7^3}{101.6^3}$

S_{TS} = True Stiffness (MPa)

S_d = Equation of difference between true stiffness and adjusted stiffness

$S_d = -561.5\ln(x) + 4974.4$

x = time of loading release (second)

By applying Equation 5-1, the corrected stiffness was calculated for every measurement obtained from the shorter span. Table 5-4 shows the percent difference between true stiffness and corrected stiffness for each sample at 60s and 120s, with the maximum percent different between true stiffness and corrected stiffness being around 5%. This is evidence that corrected stiffness is very consistent with true stiffness and that Equation 5-1 can be used for translating the BBR testing results for 100-mm diameter cores using a shorter span.

Table 5-4. Difference Between True Stiffness and Corrected Stiffness at 60s and 120s

Sample	S_{TS} (MPa)	S_{CS} (MPa)	Difference (MPa)	Percent Difference
60s				
SR89	9845.6	9513.9	331.6	3.43%
SR172	10451.9	10272.0	179.8	1.74%
I84	9915.0	10312.3	-397.3	-3.93%
120s				
SR89	8676.4	8395.7	280.7	3.29%
SR172	9217.0	9173.1	44.0	0.48%
I84	8583.1	9073.8	-490.7	-5.56%

5.3 Field Core Sample Analysis

Five beams were obtained from SR89 and SR172, and 10 beams were obtained from I84. The resultant 20 testing beams were all tested using the BBR with the shorter span at -18°C (binder PG +10°C). The BBR testing results at 60s after the removal of outliers without adjustment are shown in Table 5-5. Using Equation 5-1, the BBR outputs were adjusted to the corrected stiffness (Table 5-6). A separate set of regular (i.e., 127-mm long) SGC-made beams from SR89, SR172, and I84 was tested at the UDOT Central lab for their creep stiffness at -18°C. The creep stiffness measurements were recorded in Table 5-6. Both the corrected stiffness for the field core samples and the stiffness for lab compacted samples were compared at 60s and 120s. Thanks to the time-temperature superposition principle, testing at longer times (120s) also represents testing at a higher temperature or testing a lower grade binder; thus, more data can be used in the analysis. The results are shown in Table 5-6. Using the data in Table 5-6, the stiffness relationship between SGC cylinders and field core samples can be plotted in Figure 5-7.

Table 5-5. Stiffness for Each Sample after Removing Outliers at 60s and -18°C

SR172		**SR89**		**I84**	
Sample Size	5	**Sample Size**	5	**Sample Size**	10
Average Stiffness	21265.5	**Average Stiffness**	17952.2	**Average Stiffness**	15079.8
Standard Deviation	1774.3	**Standard Deviation**	2200.2	**Standard Deviation**	1309.8
CV	0.1	**CV**	0.1	**CV**	0.1
Sample Size after remove outliers	5	**Sample Size after remove outliers**	3	**Sample Size after remove outliers**	8

Table 5-6. Percent Difference of Stiffness Between Field Core Samples and Lab Compacted Samples

Sample	Stiffness of Lab SGC Samples at -18C (MPa)	Corrected Stiffness of Field Core Samples at -18C (MPa)	Percent Difference
60s			
SR172	12646.3	14144.0	-11%
SR89	11290.0	12357.1	-9%
I84	12770.5	10808.0	17%
120s			
SR172	11335.9	12721.8	-12%
SR89	10012.0	11077.7	-10%
I84	11445.5	9610.7	17%

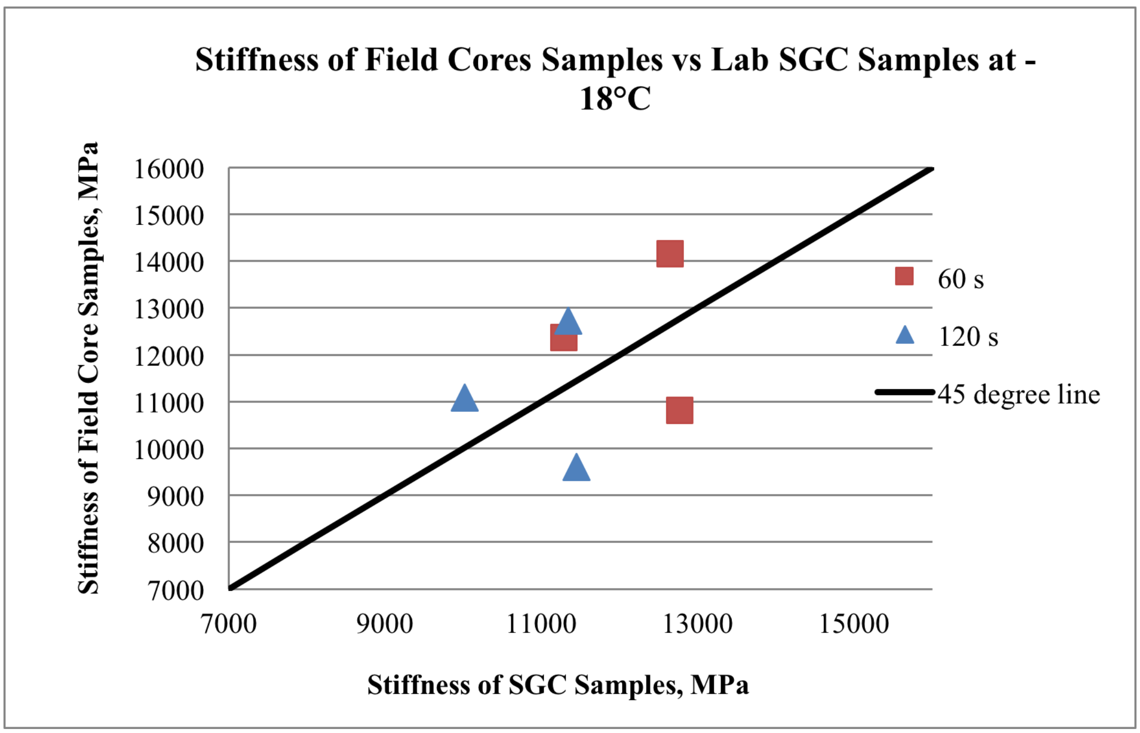

Figure 5-7. Relationship between stiffness of field core and lab compacted sample.

As shown in Figure 5-7, most of the stiffness results are close to the 45-degree line. This indicates that the corrected stiffness for field core samples is close to the true stiffness from SGC samples. Differences between cores and laboratory samples are expected because the field cores experience a different conditioning procedure including compaction and long-term aging, causing the field core samples to be different than their lab counterparts. The stiffness differences between field core samples and SGC cylinders are between 9% and 17%, as shown in Table 5-6. These percent differences are relatively small, within the accepted error in testing. They indicate that Equation 5-1 is accurately enough to represents the data. Given the above analysis, the BBR test may be used in testing beams from 100-mm field core samples, given the proposed modifications.

5.4 Summary

Based upon the investigation and analysis of asphalt mixtures tested using the BBR using samples from SGC cylinders and field core samples, several conclusions can be summarized.

1. The BBR can successfully be used to test mixtures and predict low-temperature performance. Measurements from SGC samples showed the asphalt mixtures with high creep stiffness and low m-value are more susceptible to thermal cracking. These samples are the same samples normally obtained for volumetric testing; thus, no new samples would be needed if this procedure were to be used on a regular basis for quality control or quality acceptance.
2. The developed methodology for 100-mm diameter field cores can provide accurate creep stiffness measurements comparable to the values obtained from

150-mm diameter SGC samples. While normal samples obtained from 150-mm diameter cylinders are still preferable, smaller cores resulting in smaller holes in the road can still be used.

3. The creep stiffness of beams from field core is about 10% higher than the lab prepared SGC cylinder for the same mix design. These differences are likely caused by differences in conditioning (i.e., aging or compaction) and should be further investigated.

CHAPTER 6

CONCLUSIONS

6.1 Summary

The repeatability and material efficiency studies of the BBR test were successfully conducted. SGC samples were cut into a number of testing beams, and tested using the BBR at different labs and with different testing time intervals. These tests showed that results were consistent between the UofU and UDOT labs, and that the long testing interval did not have any significant influence on the BBR testing results. Additional experiments that were performed at the UofU lab revealed that BBR testing beams can be reused without compromising the consistency of its results. Both SGC samples and field core samples were used to obtain samples for the material efficiency study. The testing results from the SGC samples showed a clear relationship with field performance. Difficulties measuring the short beams using the BBR that were cut from field core samples were overcome by adding two additional supports and using an equation to adjust the results. Results were compared between SGC samples and field core samples from the same mix, and the ability of the BBR to test field core samples was evaluated.

6.2 Conclusions

The BBR test, as a recently adopted low-temperature performance testing method for asphalt mixtures, not only provides same-day testing results, but also shows undoubtable advantages compared to other existing methods. This study of repeatability and material efficiency of the BBR test provided additional evidence demonstrating that the BBR test is a very practical method that can be adopted for low-temperature performance testing as part of quality control procedures for asphalt mixtures.

The results of the repeatability study guaranteed the consistency of BBR test results. A batch of BBR tests can be performed for quality control operations in minimal time, without needing to worry about inaccuracies and errors potentially caused by performing BBR tests across different labs, at different testing intervals, and/or repeatedly on the same specimens. This repeatability study reduces workload of any DOT and highway agency quality control team in preparing additional asphalt mixture samples when the results of the first BBR test are not ideal, in that they can verify their results later on without needing to create new samples. This study not only provided support for the notion that the BBR test meets the time efficiency requirements of a standard specification, but also indicated that the BBR test is a materially efficient test.

In addition to the repeatability study, the specific study on verification of the material efficiency of the BBR test clearly showed its ability to test two types of already-collected samples. However, the procedures and setups that were used to test 100-mm field core samples need to be further discussed. According to Three Point Beam Theory (Equation 3-1), for beams with same width and thickness, there is a linear relation which exists between span length and deflection, and between load and deflection, if one or another holds constant. This indicates that the stiffness of short beams should be directly obtained only by substituting the default span length with the measured span length of short beams. It was observed that the direct substitution of short beam testing results always resulted in a smaller stiffness relative to the true stiffness (long beam stiffness), and their difference fit well in a trend line (Figure 5-4 to Figure 5-7). This finding violated beam theory and additional experiments were performed to for linearity in the results.

Two sets of BBR tests were performed at 18°C on each of the three beams that were cut from SR89 samples under loads of 1000mN, 2000mN, 3000mN, and 4400mN. The first set of tests was done with a longer span, and the second set of tests was done with a shorter span. Two figures were plotted with trend lines based on the average results of the three beams. Figure 6-1 shows the deflection versus loads for both long and short span testing. It shows that the deflection linearly increases with the load increase when the span length is constant, which indicates it is a linear elastic system and the magnitude of measuring load should not affect results. This experiment provided a clear relationship between deflection and applied load, and an assumption can be made that the difference between short and long beam may not be a result of violating beam theory. Without further investigation of this issue, the difference may be thought to be caused by the composite nature of the materials, machine errors, or calibration bias.

6.3 Recommendations

More questions need to be further addressed and verified:

1. Determining the repeatability of the BBR test during the steric hardening

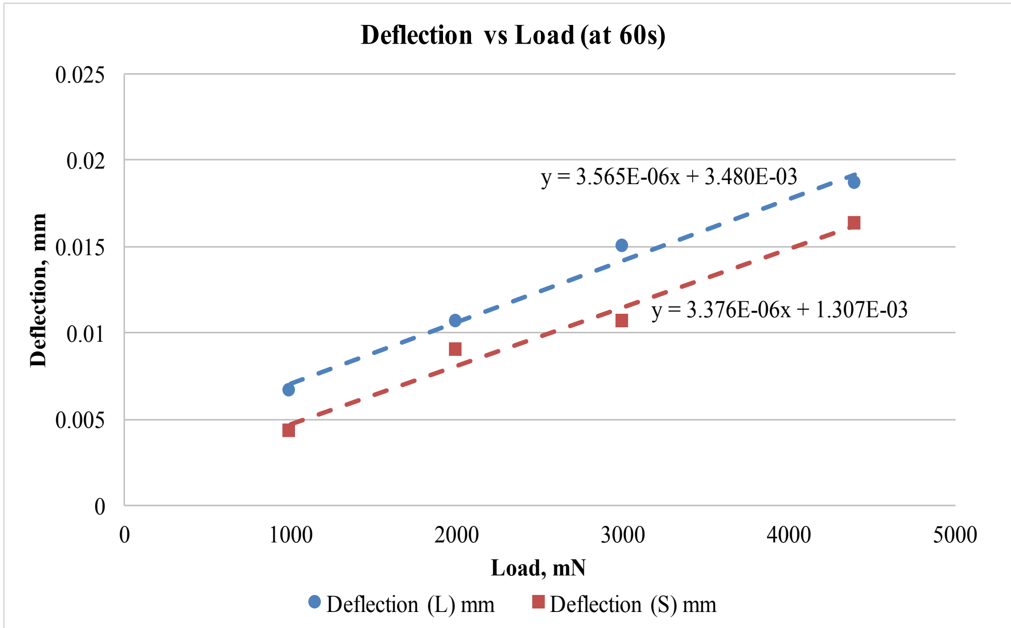

Figure 6-1. Deflection varies with loading.

period (within 48 hours from sample creation) and also studying the steric hardening effect on asphalt mixtures.

2. Performing long-term repeatability study on the BBR test in order to further investigate the performance of the BBR test.
3. It is still important to further study the difference between beams with short span and long span. The beam theory still needs to be further verified with replicable samples.
4. It is suggested to verify the BBR testing results using developed short span procedures with the testing results from other low-temperature performance tests, such as the IDT, to further prove the validity of the BBR short beam testing procedure.

APPENDIX

UNPAIRED T-TEST FOR MULTI-LABORATORY COMPARISON

A.1 Procedures for T-Test

1. **Parameter of interest:** The parameter of interest is the mean of the measured stiffness of beams at 60 seconds and 120 seconds for UDOT samples ($\overline{x_1}$) and U-LAB samples ($\overline{x_2}$).
2. **Null hypothesis:** $H_o{:}\overline{x_1}=\overline{x_2}$ (the mean stiffness of UDOT samples is equal to the mean stiffness of U-LAB samples, and there is no stiffness difference between both samples.)
3. **Alternative hypothesis:** $H_1{:}\overline{x_1}\neq\overline{x_2}$ (the stiffness mean of UDOT samples is not equal to the stiffness mean of U-LAB samples, and there is a stiffness difference between both samples.)
4. **Test statistic (t_o):** unpaired t-test for independent sample

$$t_o=\frac{\overline{x_1}-\overline{x_2}}{\sqrt{\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}}} \qquad \textit{Equation A1-1}$$

Where: $\overline{x_1}$ = mean stiffness of UDOT measurements (MPa)

$\overline{x_2}$ = mean stiffness of U-LAB measurements (MPa)

n_1 = number of of UDOT measurements

n_2 = number of U-LAB measurements

s_1 = variance of UDOT measurements

s_2 = variance of U-LAB measurements

5. **Significance level and degree of freedom:**

   Significance level: $\alpha = 5\%$

   Degree of freedom (d.o.f.): $$\frac{\left(\frac{s_1^2}{n_1}+\frac{s_2^2}{n_2}\right)^2}{\frac{s_1^4}{n_1^2(n_1-1)}+\frac{s_2^4}{n_2^2(n_2-1)}}$$ *Equation A1-2*

6. **Reject $\boldsymbol{H_o}$ if:** $|t_o|>t_{\alpha,n-2}$

7. **Computation:** t_o and $t_{\alpha,n-2}$ (critical value for 2-tails with significant level of 5%)

8. **Conclusion:** The null hypothesis is accepted if $|t_o|\leq t_{\alpha,n-2}$. There is no statistical difference between the stiffness mean of UDOT measurements and stiffness mean of U-LAB measurements at a significance level of 5%.

A.2 T-Test Results

The unpaired T-test results for measurements at 60 seconds and 120 seconds of multi-laboratory comparison are shown in Table A-1.

Table A-1. T-Test Results

	UDOT	**U-LAB**	**UDOT**	**U-LAB**
	60 s		**120s**	
2-Day Test				
$\bar{x}$, MPa	14153.93	14730.29	12573.52	13408.43
s^2	3185390.26	1519708.99	3460584.07	1402205.73
n	3	3	3	3
t_o	-0.46		-0.66	
d.o.f.	3.55		3.39	
$t_{\alpha,n-2}$	3.182		3.182	
Conclusion	0.46<3.182, **Accepted**		0.66<3.182, **Accepted**	
3-Day Test				
$\bar{x}$, MPa	14082.02	13992.18	12707.69	12743.61
s^2	2006748.17	944406.69	2049970.02	648177.5
n	4	5	4	5
t_o	0.11		-0.04	
d.o.f.	5.14		4.49	
$t_{\alpha,n-2}$	2.571		2.776	
Conclusion	0.11<2.571, **Accepted**		0.04<2.776, **Accepted**	
1-Week Test				
$\bar{x}$, MPa	14195.55	13749.79	12647.57	12346.33617
s^2	2061605.31	1028206.14	1264596.41	1232564.00
n	4	4	4	4
t_o	0.51		0.38	
d.o.f.	5.40		6.00	
$t_{\alpha,n-2}$	2.571		2.447	
Conclusion	0.51<2.571, **Accepted**		0.38<2.447, **Accepted**	
2-Week Test				
$\bar{x}$, MPa	15653.28	14381.85	13554.31	13193.46
s^2	2108911.25	1888149.92	1720972.23	1666171.26
n	4	4	4	4
t_o	1.27		0.39	
d.o.f.	5.98		6.00	
$t_{\alpha,n-2}$	2.447		2.447	
Conclusion	1.27<2.447, **Accepted**		0.39<2.447, **Accepted**	

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